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SINKAGE, TRIM, DRAG OF A COMMON FREELY FLOATING MONOHULL SHIP

CHAO MA, YI ZHU, HUIYU WU, WEI LI, HUIPING FU AND FRANCIS NOBLESSE

State Key Laboratory of Ocean Engineering
Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration
School of Naval Architecture, Ocean & Civil Engineering
Shanghai Jiao Tong University, Shanghai, China
e-mail: chaoma1988dr@163.com

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Abstract. A practical method — well suited for early ship design and hull form optimization — for estimating the sinkage, the trim and the drag of a freely-floating common monohull ship at moderate Froude numbers $F \leq 0.45$ is considered. The sinkage and the trim are realistically estimated via two alternative simple methods: an experimental approach based on an analysis of experimental measurements (involving no flow computations), and a numerical approach based on a practical linear potential-flow theory (the Neumann-Michell theory) that only requires simple flow computations for the hull surface Σ_0^H of the ship at rest. The drag is also estimated in a simple way, based on the classical Froude decomposition into viscous and wave components: well-known semi empirical expressions for the friction drag, the viscous drag and the drag due to hull roughness are used, and the wave drag is evaluated via the Neumann-Michell theory. The drag is more sensitive to the hull position than the sinkage and the trim. Accordingly, it must be computed for a 'dynamic' ship hull surface Σ_{st}^H that accounts for sinkage and trim effects, although the hull surface Σ_{st}^H does not need to be very precise. In fact, the total drag computed for the hull surface Σ_{st}^H chosen as the hull surface Σ_1^H predicted by the numerical approach, or as the hull surface Σ_a^H predicted by the even simpler experimental approach, are nearly identical. Moreover, the drag of the hull surface Σ_1^H and the (nearly identical) drag of the hull surface Σ_a^H are significantly higher, and also in much better agreement with experimental measurements, than the drag of the hull surface Σ_0^H of the ship at rest at high Froude numbers.

1 INTRODUCTION

The drag experienced by a ship is a critical element of ship design. Accordingly, the prediction of the flow around a ship hull that advances at a constant speed along a straight path, in calm water of large depth and lateral extent, is a classical basic ship hydrodynamics problem that has been widely considered in a huge body of literature, e.g. [1].

The drag of a ship is well known to be influenced by several complicated flow features, including (i) viscous effects and the related flow separation that typically occurs at a ship stern, notably a transom stern, (ii) nonlinear effects and the related wavebreaking at a ship bow, (iii) hull roughness effects for full-scale ships, and (iv) the influence of sinkage and trim for a freely floating ship. This study examines the influence of sinkage and trim on the drag of a common generic freely floating monohull ship (free to sink and trim) at $F \equiv V/\sqrt{gL} \leq 0.45$, where V and L denote the speed and the length of the ship, and g is the acceleration of gravity.

The pressure distribution around a ship hull surface Σ^H that advances at a constant speed V in calm water evidently differs from the hydrostatic pressure distribution around the wetted hull surface Σ_0^H of the ship at rest, i.e. at zero speed $V = 0$. Consequently, the ship experiences a hydrodynamic lift and pitch moment, and a related vertical displacement and rotation of Σ_0^H that are commonly called sinkage and trim, as well known and widely considered in the literature; e.g. [2-10].

As already noted, alternative methods for evaluating the sinkage and the trim, as well as the drag, experienced by a freely floating ship have been considered in the literature. In particular, the approach considered in [2-8] involve iterative flow computations for a sequence of hull positions, which is ill suited for routine practical applications to early ship design and hull form optimization, and are unnecessary at Froude numbers $F \leq 0.45$, as shown in [11]. Practical methods for estimating the sinkage, the trim and the drag of a ship, notably methods that do not require iterative flow computations for a sequence of hull positions, are useful (if not necessary) at early design stages and for hull form optimization.

[11] considers two simple approaches — an 'experimental approach' and a 'numerical approach' — for estimating the sinkage and the trim of a typical freely floating monohull ship that advances in deep water at a Froude number $F \leq 0.45$.

The experimental approach is based on an analysis of experimental measurements reported in the literature for 22 models of monohull ships. This analysis of experimental data yields particularly simple approximate analytical relations that explicitly predict the sinkage and the trim experienced by a monohull ship — without flow computations — in terms of the Froude number F, the beam B, the draft D, and the block coefficient C_b.

The numerical approach only involves linear potential flow computations for the ship at rest, i.e. for the wetted hull surface Σ_0^H, rather than for the mean wetted hull surface Σ^H of the ship at its actual position. This practical simplification stems from the fact that the sinkage and the trim are mostly determined by the pressure distribution over the lower part of the ship hull surface, and consequently are not highly sensitive to the precise position of the ship. A linear potential flow method is used in the numerical approach considered in [11].

Both the simple numerical approach and the even simpler experimental approach are found in [11] to yield realistic predictions of sinkage and trim at $F \leq 0.45$.

A practical approach for determining the drag of a typical freely floating monohull ship at a moderate Froude number $F \leq 0.45$ is considered here. Specifically, classical semiempirical relations for the friction drag, the viscous drag and the drag due to hull roughness are used, and the wave drag is evaluated via a practical linear potential flow method, as given in [12]. The drag is much more sensitive to the hull position than the sinkage and the trim (for a simple reason explained in section 2). Accordingly, the drag must be computed for a 'dynamic' ship hull surface Σ_{st}^H that accounts for sinkage and trim effects. Specially, the hull surface Σ_{st}^H can be chosen as the hull surface Σ_1^H that is predicted by the numerical approach, or as the hull surface Σ_a^H that is predicted by the even simpler experimental approach, as illustrated via numerical computations in section 6.

Moreover, the drag of the hull surface Σ_1^H and the (nearly identical) drag of the hull surface Σ_a^H are significantly higher — and also much closer to experimental measurements for the Wigley, S60 and DTMB5415 models — than the drag of the hull surface Σ_0^H of the ship at rest at high Froude numbers F (within the constraint $F \leq 0.45$ considered here). These numerical results suggest that sinkage and trim effects, significant at Froude numbers $0.35 \leq F$, on the drag of a typical freely floating monohull ship can be well accounted for in a practical way that only requires linear potential flow computations, without iterative computations for a sequence of hull positions.

Hereafter, coordinates and flow variables are made nondimensional in terms of the gravitational acceleration g, the water density ρ, and the length L and the speed V of the ship. The Cartesian system of nondimensional coordinates $(x, y, z) \equiv \mathbf{x} \equiv \mathbf{X}/L$ is attached to the moving ship. The x axis is chosen along the path of the ship and points toward the ship bow. The undisturbed free surface is taken as the plane $z = 0$ and the z axis points upward. The ship bow and stern are located at $\mathbf{x}_b = (0.5, 0, 0)$ and at $\mathbf{x}_s = (-0.5, 0, 0)$. The unit vector $\mathbf{n} \equiv (n^x, n^y, n^z)$ is normal to the hull surface Σ^H and points outside the ship (into the water).

The present study summarizes the analysis and the main results of the practical approaches considered in [11] and [12] for estimating the sinkage and the trim, and their influence on the drag, for a common freely-floating monohull ship at moderate Froude numbers $F \leq 0.45$.

2 BASIC RELATIONS FOR THE SINKAGE AND THE TRIM

Hereafter, the vertical displacement of a ship hull surface Σ^H from its position Σ_0^H at rest, at midship, is called 'midship sinkage' and denoted as H^m. Similarly, the vertical displacement of Σ^H at the ship bow and stern are denoted as H^b and H^s, and called 'bow sinkage' and 'stern sinkage'. Positive values of H^m, H^b or H^s correspond to downward vertical displacements of Σ^H at midship, at a ship bow or at a ship stern, respectively. The rotation of Σ^H from Σ_0^H is defined by the trim angle $\tau^\circ \equiv \tau^{rad} 180/\pi$ where the angles τ° and τ^{rad} are measured in degrees or in radians, or by the equivalent 'trim sinkage' H^τ defined as

$$2\,H^\tau \equiv L \tan(\tau^{rad}) \approx L\,\tau^{rad} \equiv L\,\tau^\circ \pi/180 \tag{1}$$

Positive values of τ°, τ^{rad}, H^τ correspond to a bow-up rotation.

The relations $H^s = H^m + H^\tau$ and $H^b = H^m - H^\tau$ hold. These geometrical identities determine the stern sinkage H^s and the bow sinkage H^b from the midship sinkage H^m and the trim sinkage H^τ that are computed in the numerical approach considered in section 3. These relations readily yield

$$H^b = 2\,H^m - H^s \;\text{ and }\; H^\tau = H^s - H^m \tag{2}$$

These relations determine the bow sinkage H^b and the trim sinkage H^τ from the midship sinkage H^m and the stern sinkage H^s that are determined in section 4 by simple analytical relations obtained via an analysis of experimental measurements.

3 NUMERICAL DETERMINATION OF THE SINKAGE AND THE TRIM

The midship sinkage H^m and the trim sinkage H^τ, where positive H^m and H^τ respectively correspond to a downward vertical displacement or a bow-up rotation of the ship hull surface

Σ_0^H as noted in section 2, are determined via the relations

$$\frac{H^m/L}{F^2} \approx \frac{C^z + \varepsilon_2\, C^{zx}}{a_0\,(1-\varepsilon_0\,\varepsilon_2)} \quad \text{and} \quad \frac{2\,H^\tau/L}{F^2} \approx \frac{C^{zx} + \varepsilon_0\, C^z}{a_2\,(1-\varepsilon_0\,\varepsilon_2)} \tag{3a}$$

Here, $\varepsilon_0 \equiv a_1/a_0$ and $\varepsilon_2 \equiv a_1/a_2$. Moreover, a_0, a_1 and a_2 denote the nondimensional area of the waterplane W_0^H of the wetted hull surface Σ_0^H and the related moments defined as

$$(a_0, a_1, a_2) \equiv \left(\frac{A_0}{L^2}, \frac{A_1}{L^3}, \frac{A_2}{L^4}\right) \equiv \int_{W_0^H} (1, x, x^2)\, dx\, dy \tag{3b}$$

The terms C^z and C^{zx} in (3a) represent the nondimensional hydrodynamic lift and moment coefficients defined as

$$(C^z, C^{zx}) = \int_{\Sigma^H} (n^z, n^x z - n^z x)\, p\, da \tag{3c}$$

where the hydrodynamic pressure p is given by the Bernoulli relation

$$p = \sqrt{(n^y)^2 + (n^z)^2}\, \phi_t + (n^x)^2/2 - (\phi_t^2 + \phi_d^2)/2 \tag{3d}$$

Here, $\phi_t \equiv \partial\phi/\partial t$ and $\phi_d \equiv \partial\phi/\partial d$ denote the velocity components along two unit vectors $\mathbf{t}$ and $\mathbf{d}$ tangent to the ship hull surface Σ^H. These tangential velocity components are evaluated here via the Neumann-Michell (NM) theory expounded in [1] and [13].

The nondimensional hydrodynamic lift and pitch-moment coefficients C^z and C^{zx} given by (3c) where the mean wetted ship hull surface Σ^H is taken as the static wetted hull surface Σ_0^H are denoted as C_0^z and C_0^{zx}. H^m and H^τ given by (3a) where C^z and C^{zx} are taken as C_0^z and C_0^{zx} are similarly denoted as H_0^m and H_0^τ. The mean wetted hull surface that is obtained from the wetted hull surface Σ_0^H of a ship at rest via a translation H_0^m and a rotation H_0^τ is denoted as Σ_1^H, and the hydrodynamic coefficients C^z and C^{zx} given by (3c) with Σ^H taken as Σ_1^H are denoted as C_1^z and C_1^{zx}. Similarly, H_1^m and H_1^τ denote the sinkage H^m and the trim H^τ determined from (3a) with C^z and C^{zx} taken as C_1^z and C_1^{zx}.

Expressions (3c) for C^z and C^{zx} show that, except for a ship hull with large flare and rake angles, the upper part of a ship hull (where $n^z \approx 0$) does not contribute appreciably to the sinkage, and that the upper hull and the parallel midbody (where $n^x z \approx 0$ and $n^z x \approx 0$) do not contribute much to the trim. Thus, the main contributions to the sinkage and the trim stem from the lower part of the ship hull surface. It can therefore be expected that the sinkage and the trim of a ship are relatively insensitive to the precise position of the ship hull, and can be realistically evaluated from the pressure distribution around the hull surface Σ_0^H of the ship at rest. This theoretical expectation is confirmed in [11] via numerical comparisons of the sinkage H^m and the trim H^τ determined for the hull surfaces Σ^H taken as Σ_0^H or Σ_1^H.

4 EXPLICIT APPROXIMATIONS FOR THE SINKAGE AND THE TRIM

The previously-noted fact that the sinkage and the trim of a ship predominantly stem from the pressure distribution over the lower part of the ship hull surface also suggests that the sinkage and the trim may not be highly sensitive to 'details' of the hull form (such as a transom stern) and the Reynolds number, and might reasonably be assumed to primarily depend on

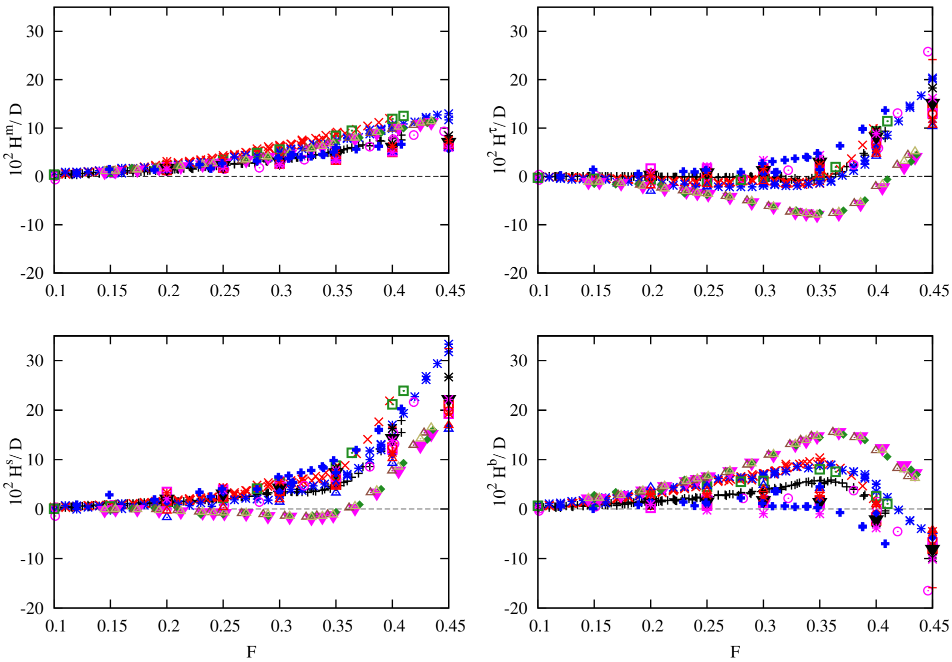

Figure 1: Midship sinkage H^m/D (top left corner), trim sinkage H^τ/D (top right), stern sinkage H^s/D (bottom left) and bow sinkage H^b/D (bottom right) for 22 models of monohull ships at $0.1 \le F \le 0.45$.

the Froude number and basic hull form parameters (such as the beam/length ratio B/L and the block coefficient C_b) that characterize the overall hull geometry. This theoretical conjecture is considered in [11] via an analysis of experimental measurements of sinkage and trim for 22 models of freely-floating monohull ships.

4.1 Experimental data base

Specifically, the experimental measurements of sinkage and trim for 22 models of monohull ships reported in publications are described and analyzed in [11].

The beam/length ratio B/L, the draft/length ratio D/L, the draft/beam ratio D/B and the block coefficient C_b for these 22 ship models vary within the relatively broad ranges

$$0.066 \le B/L \le 0.148 \ , \ 0.029 \le D/L \le 0.071$$
$$0.276 \le D/B \le 0.667 \ , \ 0.397 \le C_b \le 0.6$$

These ranges of variations of B/L, D/L, D/B and C_b correspond to a wide range of hull forms.

Fig.1 depicts the experimental measurements, for Froude numbers F within the range $0.1 \le F \le 0.45$, of the midship sinkage H^m, the trim sinkage H^τ, the stern sinkage H^s and the bow sinkage H^b for the 22 ship models. This figure shows that H^m and H^s mostly increase monotonically as the Froude number F increases. However, the variations of the trim sinkage H^τ and the bow sinkage H^b are more complicated. Accordingly, only the experimental measurements of the midship sinkage H^m and the stern sinkage H^s are analyzed. The bow sinkage H^b and the trim sinkage H^τ can be subsequently determined from H^m and H^s via the relations (2).

4.2 Midship sinkage

The variations of the experimental measurements of the midship sinkage H^m for the 22 models of monohull ships depicted in the top left corner of Fig.1 with respect to the Froude number F and the four basic hull form parameters B/L, D/L, D/B and C_b are analyzed in [11]. This analysis shows the midship sinkage H^m increases approximately like F^2 as $F \leq 0.45$ increases, is approximately proportional to $\sqrt{BD}$, and moreover increases as the block coefficient C^b increases. Specifically, the detailed analysis of experimental measurements of the midship sinkage H^m given in [11] shows that H^m can be explicitly estimated in terms of the beam B, the draft D, the block coefficient C_b and the Froude number F via the simple analytical relations

$$H^m/\sqrt{BD} \approx F^2 C^m \text{ where } C^m \equiv 0.9(C_b - 0.13) \tag{4}$$

with an accuracy of 20% in most cases and 30% in nearly all cases of a wide range of monohulls.

4.3 Stern sinkage

The variations of the experimental measurements of the stern sinkage H^s for the 22 models of monohull ships depicted in the bottom left corner of Fig.1 with respect to the Froude number F and the four basic hull form parameters B/L, D/L, D/B and C_b are analyzed in [11]. This analysis shows that the stern sinkage H^s increases approximately like the function f defined as

$$f \equiv F_*^2 \sqrt{1 + F_*^8} \text{ with } F_* \equiv F/\,0.33 \tag{5a}$$

as $F \leq 0.45$ increases, and is approximately proportional to $\sqrt{BD}$. The available experimental measurements of H^s show no convincing correlations between H^s and C^b. Specifically, the detailed analysis of experimental measurements of the stern sinkage H^s given in [11] shows that H^s can be explicitly estimated in terms of the beam B, the draft D, and the Froude number F via the simple analytical relations

$$40\, H^s/\sqrt{BD} \approx f \tag{5b}$$

with an accuracy 20% in many cases and 40% in most cases of a wide range of monohull ships, where f is given by (5a).

4.4 Explicit analytical approximations

The midship sinkage H^m and the stern sinkage H^s can then be approximately determined by means of relations (4) and (5), and the bow sinkage H^b and the trim sinkage H^τ can be determined from H^m and H^s via the relations (2). Thus, the analysis of experimental measurements considered in [11] determines H^m, H^s, H^b and H^τ via the analytical relations

$$H^m \approx 0.9\sqrt{BD}\,(C_b - 0.13)\,F^2 \tag{6a}$$

$$H^s \approx 0.025\sqrt{BD}\,F_*^2\sqrt{1+F_*^8} \text{ with } F_* \equiv F/0.33 \tag{6b}$$

$$H^b = 2H^m - H^s \text{ and } H^\tau \equiv L\tau^\circ\pi/360 = H^s - H^m \tag{6c}$$

The trim angle τ° in (6c) is measured in degrees. These relations explicitly determine the sinkage and the trim without flow computations, and are then particularly simple.

5 PRACTICAL EVALUATION OF THE DRAG

The nondimensional drag coefficient

$$C^t \equiv D/(\rho V^2 L^2) \tag{7}$$

is evaluated in [12] and here in a simple way, based on the classical Froude decomposition into viscous and wave components, as in Yang et al. (2013). Specifically, C^t is expressed as

$$C^t = C^w + C^v + C^a \tag{8}$$

where C^w represents the wave drag coefficient, C^v is the viscous drag coefficient for a smooth ship hull, and C^a accounts for the additional drag due to roughness.

The viscous drag C^v in (8) is expressed as

$$C^{\mathrm{v}} = (1+k)\,C^{\mathrm{f}} \tag{9a}$$

where C^{f} and k are the usual friction drag coefficient and form factor. The friction drag C^{f} is evaluated via the ITTC 1957 formula

$$C^{\mathrm{f}} = \frac{A^H}{2L^2}\,\frac{0.075}{(log_{10}R_e - 2)^2} \;\text{ where }\; R_e \equiv \frac{VL}{\nu} \tag{9b}$$

and A^H denotes the wetted area of the ship hull surface Σ^H. The kinematic viscosity ν is taken as $1.14 \times 10^{-6} m^2/s$ hereafter. The form factor k is estimated via the relation

$$k = 0.6\sqrt{\Delta/L^3} + 9\,\Delta/L^3 \;\text{ with }\; 0.05 \leq k \leq 0.40 \tag{9c}$$

given in [14]. Here, Δ denotes the displacement of the ship.

The roughness correction C^a in (8) is determined via the Bowden-Davison formula

$$C^a = 10^{-4}\,\frac{A^H}{2L^2}\,R \qquad \text{where }\; 4 \leq R \equiv 1050\left(\frac{k_s}{L}\right)^{1/3} - 6.4 \leq 8 \tag{10}$$

given in [15]. k_s characterizes the roughness of the hull surface, and $k_s = 0.00015$m is used here.

The wave drag coefficient C^w is determined via integration of the pressure p at the hull surface Σ^H, i.e.

$$C^w = \int_{\Sigma^H} n^x\, p\, da \tag{11}$$

where p is given by the Bernoulli relation (3d). The Neumann-Michell theory is used to compute the flow around the ship hull surface Σ^H and the related flow pressure p. Expression (11) for C^w shows that the parallel midbody section and bottom part of a ship hull surface, where $n^x \approx 0$, contribute little to the wave drag, which mostly stems from the upper parts of the bow and stern regions where $n^x \neq 0$. The drag of a ship can therefore be expected to be much more sensitive to the precise position of the ship hull than the sinkage and the trim, which are mostly determined by the pressure distribution over the hull bottom as noted earlier.

A_0^H, A_1^H and A_a^H denote the wetted areas of the hull surfaces Σ_0^H of the ship at rest or the hull surface Σ_1^H or Σ_a^H determined from the sinkage and the trim predicted by the numerical

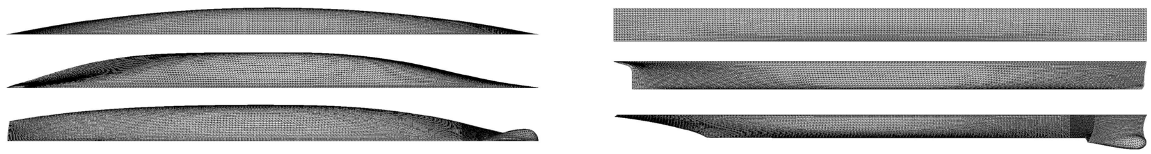

Figure 2: Side views (left) and bottom views (right) of the wetted hull surfaces Σ_0^H of the Wigley hull (top), the S60 model (middle) and the DTMB5415 model (bottom) approximated via 7,562 (Wigley), 11,542 (S60) and 12,586 (DTMB5415) flat triangular panels.

approach or the experimental approach considered in sections 3 and 4. Expression (9a) shows that differences among the wetted areas A_0^H, A_1^H and A_a^H yield differences among the friction drag coefficient C^{f}. The total drag coefficients C_0^t, C_1^t, C_a^t, the viscous drag coefficients C_0^v, C_1^v, C_a^v and the wave drag coefficents C_0^w, C_1^w, C_a^w correspond to the hull surfaces Σ_0^H, Σ_1^H or Σ_a^H, respectively.

6 ILLUSTRATIVE APPLICATIONS FOR THREE SHIP MODELS

The simple methods for determining the sinkage, the trim and the drag of a freely-floating ship given in the foregoing are now applied to three ship models: the Wigley hull, the S60 model and the DTMB5415 model. The length L of these ship models is 2.5m for the Wigley hull, 4m for the S60 model and 5.72m for the DTMB5415 model. Side and bottom views of the wetted hull surfaces Σ_0^H for these three ship models are shown in Fig.2. Half of the hull surface Σ_0^H is approximated via 7562, 11,542 or 12,586 flat triangular panels for the Wigley hull, the S60 model and the DTMB5415 model, respectively.

Fig.3 depicts the midship sinkage H^m/D and the trim sinkage H^τ/D estimated via numerical approach (3), experimental approach (6) or experimental measurements for the three ship models at $0.1 \le F \le 0.45$.

Fig.3 shows that the numerical predictions for the hull surfaces Σ_0^H or Σ_1^H are nearly identical for the midship sinkage H^m, and do not differ significantly for the trim sinkage H^τ. Moreover, these numerical predictions are in relatively good agreement with the experimental measurements. The numerical predictions for the hull surface Σ_1^H are not closer to the experimental measurements of the trim sinkage H^τ than the numerical predictions for the hull surface Σ_0^H. This finding suggests that it is sufficient to compute the flow around the 'static' ship hull surface Σ_0^H, instead of the 'dynamic' hull surface Σ_1^H, for the purpose of predicting the sinkage and the trim of common monohull ships at Froude numbers $F \le 0.45$. Fig.3 also shows that the simple analytical relations (6) yield predictions of the midship sinkage H^m and the trim sinkage H^τ that are in relatively good agreement with the numerical predictions, as well as the experimental measurements.

Fig.4 depicts the theoretical predictions of the total drag C^t, the wave drag C^w and the viscous drag C^v that correspond to the hull surfaces Σ_0^H, Σ_1^H and Σ_a^H for the Wigley hull, the S60 model and the DTMB5415 model. The experimental measurements C_e^t of the total drag C^t that are also shown in Fig.4 correspond to freely-floating ship models, and are determined via

$$C_e^t = C^r + C_0^v \tag{12}$$

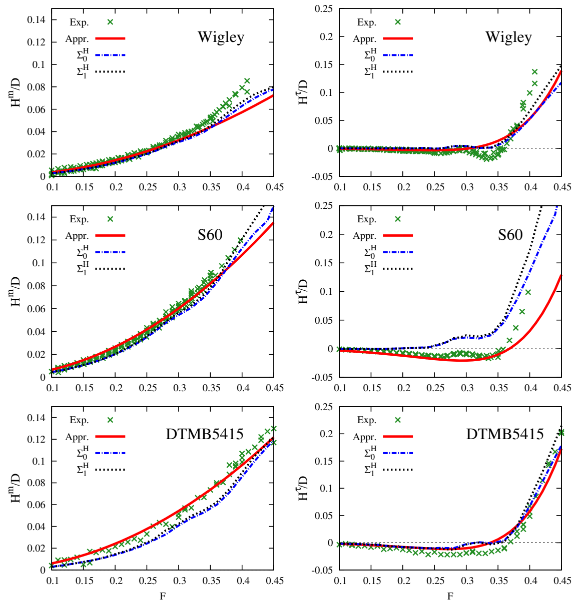

Figure 3: The midship sinkage H^m/D (left) and the trim sinkage H^τ/D (right) for the Wigley hull (top), the Series 60 model (center) and the DTMB5415 model (bottom). Experimental measurements (Exp.) are shown together with the predictions given by the analytical relations (6) obtained from an analysis of experimental measurements (Appr.) and the numerical predictions given by the Neumann-Michell theory applied to the hull surfaces Σ_0^H or Σ_1^H.

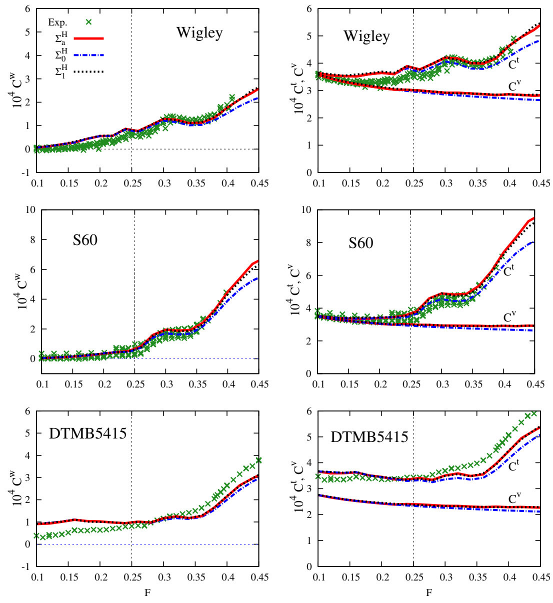

Figure 4: The left side depicts the wave drag C^w and the right side depicts the viscous drag C^v and the total drag C^t for the Wigley hull (top), the S60 model (center) and the DTMB5415 model (bottom). Experimental measurements (Exp.) are shown together with the theoretical predictions (8)-(11) applied to the hull surfaces Σ_a^H, Σ_0^H or Σ_1^H.

where C^r denotes the residual drag of the freely-floating ship model and C_0^v is the viscous drag of the hull surface Σ_0^H of the ship at rest.

Fig.4 shows that differences among the theoretical drag coefficients C^t, C^w and C^v for the hull surfaces Σ_1^H and Σ_a^H are practically negligible. Moreover, the total drags C^t of the hull surfaces Σ_1^H and Σ_a^H are in reasonable overall agreement with the experimental measurements C_e^t. Fig.4 also shows that differences between the theoretical drag coefficients C^t, C^w, C^v for the hull surfaces Σ_1^H or Σ_a^H and the hull surface Σ_0^H of the ship at rest are fairly small for $F < 0.25$, but increase rapidly for $0.25 < F$. Sinkage and trim effects on the drag can then be ignored for $F < 0.25$, but can be significant for $0.25 < F$.

Experimental measurements, denoted as C_e^t, of the total drag C^t for a freely-floating ship are now compared to the corresponding theoretical predictions C_0^t or C_1^t for the ship hull surfaces Σ_0^H or Σ_1^H. The relative differences between the experimental measurements C_e^t and the corresponding theoretical predictions C_0^t or C_1^t for the ship hull surfaces Σ_0^H or Σ_1^H are

$$e_0^t = (C_e^t - C_0^t)/C_0^t \quad \text{and} \quad e_1^t = (C_e^t - C_1^t)/C_1^t \tag{13}$$

The relative errors e_0^t and e_1^t are associated with the hull surface Σ_0^H, which ignores sinkage and

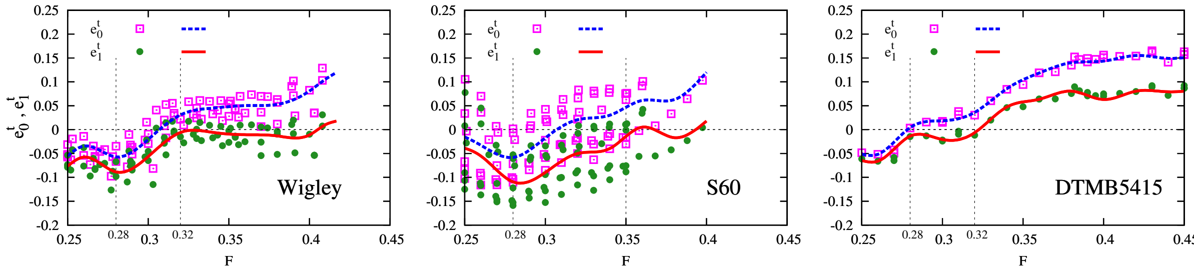

Figure 5: Relative errors e_0^t and e_1^t, and corresponding smoothing spline fits, between experimental measurements of the total drag C^t and theoretical predictions for the hull surface Σ_0^H of a ship at rest or the hull surface Σ_1^H that accounts for sinkage and trim effects.

trim, or the hull surface Σ_1^H that accounts for the influence of sinkage and trim on the drag. Thus, the errors e_0^t and e_1^t provide a basis for validating the theoretical method considered here to account for the influence of sinkage and trim on the drag of a freely-floating ship.

Fig.5 depicts the relative errors e_0^t and e_1^t for the Wigley, S60 and DTMB5415 models within $0.25 < F < 0.45$ for which sinkage and trim have a significant influence on the drag. The dashed and solid lines in Fig.5 are smoothing spline fits that correspond to the experimental values of e_0^t (squares) or e_1^t (circles). The errors e_0^t increase for $0.28 < F$ and are significant for $0.35 < F$. Indeed, the errors e_0^t are larger than 10% for $0.4 < F$. The errors e_1^t are much smaller than the errors e_0^t for the Wigley hull and the DTMB5415 model at $0.32 < F$, and for the S60 model at $0.35 < F$. Specifically, the errors e_1^t vary within ±2% for the Wigley and S60 models in the Froude number ranges $0.32 < F$ or $0.35 < F$, and vary within ±7% for the DTMB5415 model at $0.32 < F$.

7 CONCLUSTIONS

The influence of sinkage and trim on the drag of a common freely floating monohull ship has been considered. The comparisons of experimental measurements and theoretical computations reported for the Wigley, S60 and DTMB5415 models suggest that the sinkage and the trim experienced by common monohull ships are small, and have limited influence on the drag, for Froude numbers $F < 0.25$. However, the sinkage and the trim, and their influence on the drag, increase rapidly for $0.25 < F$, and are significant for the highest value $F = 0.45$ of the Froude number range $0.1 \leq F \leq 0.45$ considered here. Sinkage and trim effects should then be considered within the design process, arguably even at early design stages and for hull form optimization.

Accordingly, practical methods suited for routine applications to ship design have been considered in [11] and here to determining the sinkage, the trim and the drag. Specifically, the sinkage and the trim are determined via two simple alternative methods, previously considered in [11]. These two methods yield predictions of sinkage and trim that do not differ greatly, and moreover are in reasonable agreement with experimental measurements for a broad class of monohull ships. The drag is similarly evaluated here in a simple way, based on the classical Froude decomposition into viscous and wave components.

One of the two simple alternative methods considered in [11] and here to determine the sinkage and the trim is a numerical method. This method only involves linear potential flow computations (the Neumann-Michell theory is used) for the wetted hull surface Σ_0^H of the ship at rest, instead of the 'dynamic' hull surface Σ_1^H, which is determined from flow computations for the hull surface Σ_0^H. This notable simplification stems from the fact that the sinkage and the trim are primarily determined by the pressure distribution over the lower part of the ship hull surface, and therefore are not highly sensitive to the precise position of the ship.

The other method considered in [11] and here to determine the sinkage and the trim is based on an analysis of experimental measurements (for 22 ship models). This alternative method yields explicit analytical relations for the sinkage and the trim in terms of the Froude number F, the beam B, the draft D, and the block coefficient C_b, and thus requires no flow computations.

As already noted, the drag is also estimated here in a simple way, based on the classical Froude decomposition of the drag into viscous and wave components. The wave drag is largely determined by the pressure distribution on the bow and the stern of a ship, and is therefore much more sensitive to the precise position of the ship hull than the sinkage and the trim, which are mostly determined by the pressure distribution over the hull bottom as already noted. This basic difference explains why the sinkage and the trim of a ship can be realistically estimated from flow computations around the hull surface Σ_0^H of the ship at rest, whereas the drag must be evaluated for a 'dynamic' ship hull surface Σ_{st}^H that accounts for the sinkage and the trim experienced by the ship.

However, the hull surface Σ_{st}^H does not need to be very precise. Indeed, a main result of the numerical computations reported here for the Wigley, S60 and DTMB models is that the hull surface Σ_a^H defined by the explicit analytical relations (6) and the hull surface Σ_1^H determined from potential flow computations for the hull surface Σ_0^H of the ship at rest have nearly identical total drag coefficients C^t. Moreover, C^t determined from the hull surface Σ_a^H or Σ_1^H are significantly higher than the drag C_0^t predicted for the hull surface Σ_0^H of the ship at rest.

Moreover, and most importantly for practical applications, the drag coefficients predicted for the hull surfaces Σ_a^H or Σ_1^H are much closer to experimental measurements than the drag of the hull surface Σ_0^H of the ship at rest for the Wigley, S60 and DTMB5415 models at Froude numbers for which sinkage and trim effects are significant, as illustrated in Fig.5.

This finding provides a partial validation of the simple approach considered here, and suggests that the influence of sinkage and trim on the drag of a freely floating monohull ship at $F \leq 0.45$ can be determined in a very simple way well suited for routine applications to design, including at early stages and for optimization. In particular, if the analytical relations (6) are used to estimate the sinkage and the trim, prediction of the drag of a freely floating ship only requires a computation of the flow around the hull Σ_a^H, i.e., a single (linear potential) flow computation per Froude number.

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